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Overview of the state of technique for PV inverters used in low voltage grid-connected PV systems: Inverters above 10 kW☆

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ABSTRACT

An analysis has been made of the most important electrical parameters related to photovoltaic grid-connected inverters above 10 kW. To achieve this, a compilation of up to fifty manufacturers, various brands and up to five hundred different models has been prepared and updated to February 2009. Datasheet and manuals have been compiled, noting down their electrical output and input characteristics. Different and important aspects with respect to performance of some PV grid-installation have been analyzed: the number of different models for values of power; topology option; operational DC parameters range (such as nominal power, maximum power, nominal current, voltage), operational AC parameter range (such as nominal power, maximum power, nominal current, voltage), inverter conversion efficiency vs. nominal power and normalised inverter size and weight.

Contents

1. Introduction

Currently the management of energy sources represents a fundamental problem for the development and prosperity of any community. As a result, two major problems exist: diminishing of energy sources and the atmospheric pollution from the residues from conventional sources. Taking both factors into consideration, it can be argued that it is necessary to optimize energy resources through the use of alternative energy sources. The main characteristics of such sources include their renewability and their limited contribution to contamination. Photovoltaic solar energy is in this category and its use has also notably increased in industry over the past few years.

In recent decades there has been an increasing interest in the use of low voltage grid-connected PV systems, conditioned by new incentives from different countries [1,2]. An essential element in those systems is the inverter, that is, the element which converts, in an efficient way, sinusoidal AC current waveform at its output so that it may be connected and synchronized to the utility network [3–14].

2. State of the technique of photovoltaic grid-connected inverters below 10 kW nominal power

In order to carry out this study, a list of five hundred models different from the inverter has been compiled. This has been

☆ Related past papers: Overview of the legislation of DC injection in the network for low voltage small grid-connected PV systems in Spain and other countries. Renewable and Sustainable Energy Reviews 2008;12(February (2)):575–83. V. Salas, E. Olías, M. Alonso, F. Chenlo; DC current injection into the network from PV inverters of <5 kW for low-voltage small grid-connected PV systems. Solar Energy Materials and Solar Cells 2007;91(May (9)):801–6.

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distributed into two groups that are based on their nominal AC power: inverters below 10 kW and inverters up to 10 kW.

With respect to grid inverters there are typically three possible inverter scenarios for a PV grid system: single central inverter, multiple string inverters and AC modules. The choice is given mainly by the power of the system. Therefore, AC module is chosen for low power of the system (around 100 W typical), [15]. And a single central inverter or multiple string inverters will be chosen depending on the designer. Technically it is possible to use both topologies.

However, in this article inverters above 10 kW will be analyzed. In this way, forty-nine brands of different inverters have been compiled, resulting in up to four hundreds fifty and seven different models.

The following brands were been collated: ACE, Advanced Energy Industries, AEG, Aixcon, Aros, Ballard, BP Solar/Trace, Conergy, Danfoss, Delta Energy, Disco, Elettronica Santerno, Energetica, Exendis, Fronius, Greenpower, Hefei, Helios, Hinergy, Ingeteam, Invertomatic, Italcoel, JEMA, Kako, Leonics, Mitsubishi, Omron, Phoenixtec, Power One, Power Solutions, PV Powered, Refu, Riello, Rudolf Fritz, Santerno, Satcon, Sharp, Siel, Siemens, SMA, Solar Konzept, Solectria, Solutronic, Sputnik, Sun Power, Suntechnics, Suntension, Sunways, Xantrex.

In order to determine the current technology of inverters, up to fifty manufacturers and up to five hundred different models were prepared and updated to February 2009. Datasheet and manuals were compiled noting down their electrical output and input characteristics.

Firstly, inverters were also analyzed according to transformer options. These can therefore be divided into three groups: 50/60 Hz LF transformers, 70%, HF transformers, 7%, and transformer-less, 23%. As can be deduced from this data, there is currently a clear tendency in LF option, for this power range. However, nowadays a great number of inverters are transformerless inverters, something not usual some years ago. Within of every group FET, IGBT and even Thyristor implementation were found.

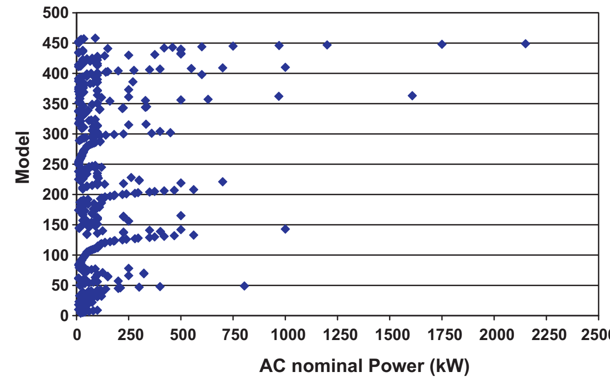

Fig. 1. Distribution of the models in function to AC nominal power (kW).

Later, different parameters' inverters were analyzed. These are very useful for PV plant designers and can limit the size of the PV array, for instance. Those can fall into two main categories: those that relate to the input inverter and those that concern the output inverter.

2.1. Output electrical parameters

Output electrical inverter parameters relate to the AC output inverter. Different output parameters such as nominal power, Pnominal, maximum power, PMax, nominal current, Inom, maximum current, Imax, output voltage, Voutput, Type (Phases) and frequency, Freq. (Hz), have been analyzed [16].

From this data it is possible to see the distribution in function on AC nominal power (kW), Fig. 1. In addition, Fig. 2 shows the distribution for every transformer option. As can be observed, the distribution is very heterogeneous.

This data also allows us to deduce that within this power range, there are one hundred and fifty-seven different values of AC

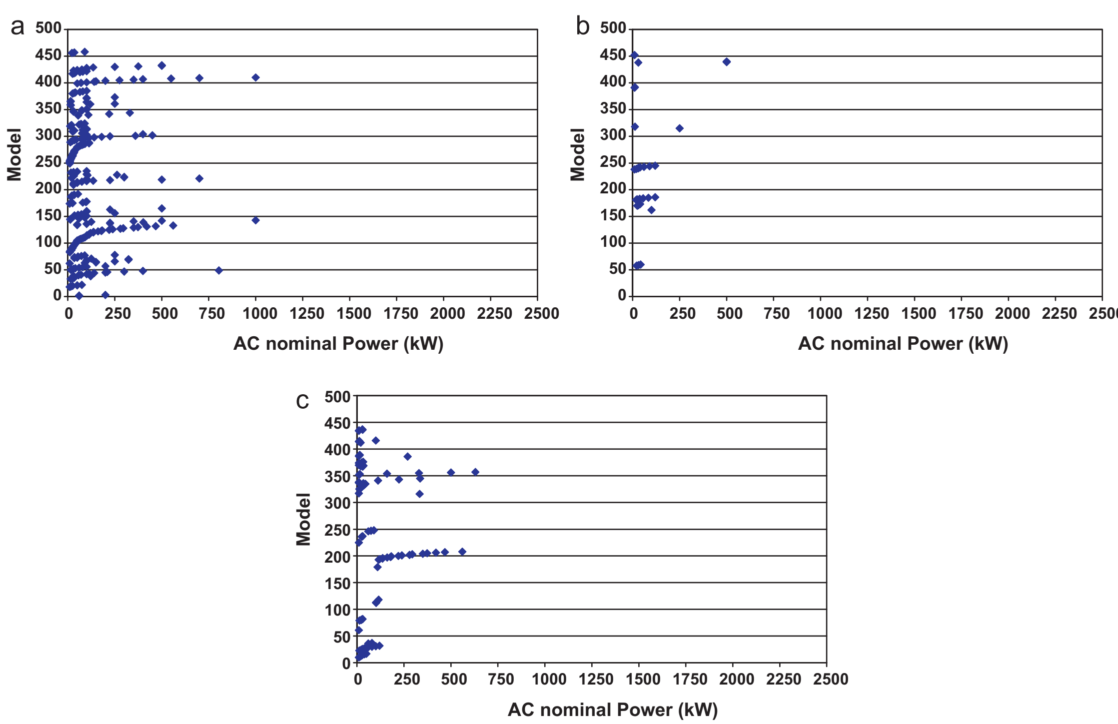

Fig. 2. (a) Distribution of the models in function to AC nominal power (kW) for inverters with LF transformer. (b) Distribution of the models in function to AC nominal power (kW) for inverters with HF transformer. (c) Distribution of the models in function to AC nominal power (kW) for inverters without transformer.

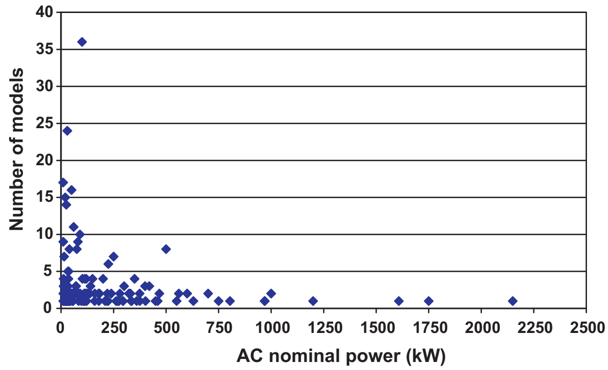

Fig. 3. Number of the different models vs AC nominal power (kW).

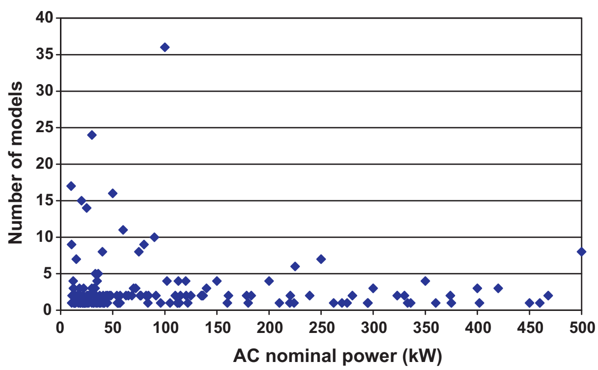

Fig. 4. Number of the different models vs AC nominal power (kW).

nominal power that oscillate between 10 and 2150 kW. The number of models for each value of nominal AC power is represented in Figs. 3 and 4. In addition, from Fig. 5, it can be seen that the most of the inverters studied stay between 10 and 100 kW (in fact 71% of them do so). It can also be inferred that the maximum number of models for the same power corresponds to 100 kW, with thirty-six models (which represents 12.16%) followed by the inverters of 50 kW (6.42%) and 30 kW (5.41%), Fig. 6.

After this, the next analysis was of the inverter distribution with respect to the number of phases (single-phase/three-phase) and the operation frequency (50/60 Hz). Results show that 98% corresponds to three-phase inverters, as was expected for this range of power. Only 7 models operate as single-phase inverters.

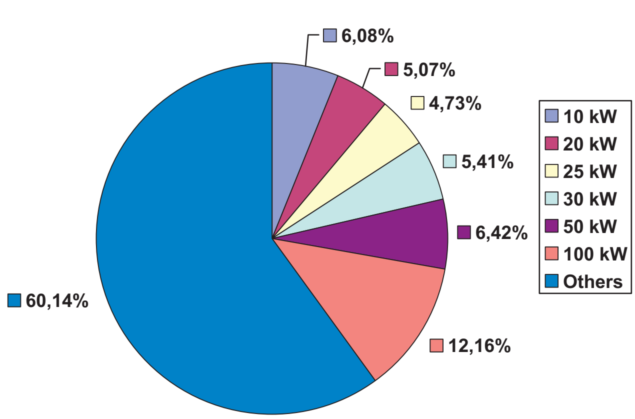

Fig. 5. Distribution of the number of the different models (%).

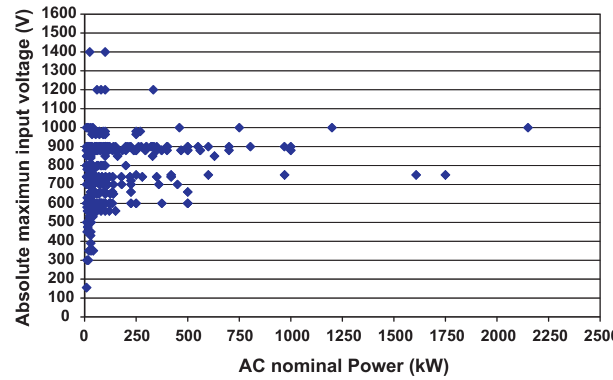

Fig. 6. Absolute maximum input voltage of inverters (V) vs. AC nominal power (kW).

Next two hundred and forty-two operate at 50/60 Hz, 53%. One hundred and forty-eight, 33% operates at 50 Hz; and sixty-one of them operate at 60 Hz, 14%.

With respect to AC output voltage, ten different voltages were found: 140, 202, 208, 230, 240, 270, 300, 400, 480 and 20,000 Vac. However, the output voltage most used was 400 Vac (in a 79% of them); 208 Vac, 7% and 480 Vac, 5%.

2.2. Input electrical parameters

Input electrical parameters relate to DC input inverter [17]. They are as follows: the maximum input operating voltage, the minimum voltage for obtaining the maximum power point and the maximum voltage for obtaining the maximum power point. These parameters are totally relating to sizing of the PV array.

According to absolute maximum input voltage it can be seen in Fig. 6 that the maximum voltage range is very broad, between 155 and 1400 V. This means that the same number of PV array of modules for all inverters cannot always be installed. In addition, it has to be taken into account that nowadays the market is generally focused on obtaining more powerful modules. As well, there is an increasing emphasis on greater value of open circuit voltage and maximum voltage point. More often than not it is very difficult find them (and more expensive).

In addition, it can be deduced that there is no relation between absolute maximum voltage and AC nominal power of inverter. That is to say, there are inverters with a high maximum voltage and low AC nominal power. Everything depends on the topology used in every inverter.

Additionally the range of maximum voltage was analyzed for inverters with different options of transformers: LF, HF and transformerless, Fig. 7a–c, respectively. As can be viewed the ranges are: for inverters with LF transformer (155–980); for inverters with HF transformer (350–880) and for transformerless inverters (430–1200 V). As well, it can be viewed that there is no relation between maximum voltage and different options of transformers of inverter.

Another interesting parameter analyzed is the maximum power point tracking implemented by grid-inverters, [18–20]. Firstly, it can be proved that nowadays all inverters have a module which seeks the maximum power point (MPP) of the PV generator. Because if inverter does not operate in the MPP the installation will present production loss. However the manufacturers do not give the MPP algorithm used (or at least their name).

That MPP is characterized by a current and voltage values. So, in order to be versatile one can connect different combination of PV array to inverter. Thus for every inverter there will be a range voltage for which the maximum power point tracking is suitable. That range is defined between the minimum and maximum MPP voltage.

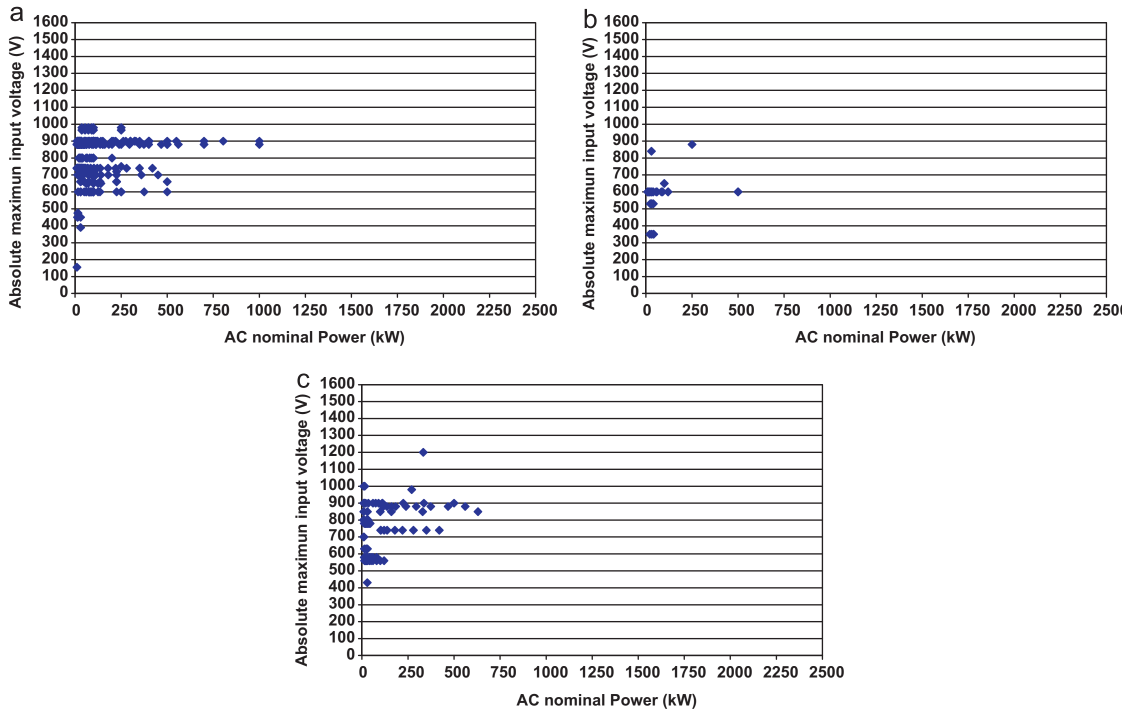

Fig. 7. (a) Absolute maximum input voltage for inverters with LF transformers. (b) Absolute maximum input voltage for inverters with HF transformers. (c) Absolute maximum input voltage for inverters with transformerless.

From our study of inverters, it can be seen that the minimum MPP voltage fluctuates between 105 and 680 V, Fig. 8. At the same time the maximum voltage fluctuates between 155 and 1200 V, Fig. 9. Also Fig. 10 shows the difference between maximum and minimum VPP voltage vs AC nominal power, that fluctuates between 50 and 650 V. As can be seen there is a lot of heterogeneity between them.

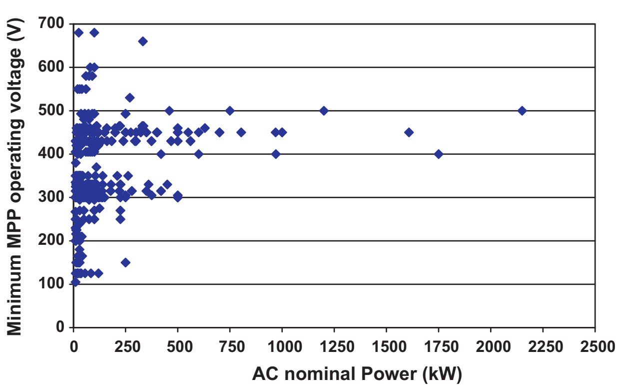

Fig. 8. Minimum power point operating voltage (V) vs AC nominal power (kW).

As well, other parameters such as efficiency have been analyzed. The electrical conversion efficiency is defined as $\eta_{inv} = P_{AC}/P_{DC}$, where P_{AC} is the inverter output power and P_{DC} is the inverter input power. This parameter is strongly important because "manages" the energy into the grid. In general, efficiency has been increasing continuously during the last few years. Such efficiency (%) varies with the photovoltaic output power (W), Fig. 11.

Related to efficiency, three parameters were found in the catalogues and manuals: the efficiency (although in fact is the maximum efficiency), the California Energy Commission conversion efficiency and the European efficiency.

The maxima efficiency (%) is the maximum value found for all range of power (W), for every inverter. It is a value that by itself offers very little information. Because, it is not the same to have a high maximum efficiency for a low power (%) than for a high power (%). But in catalogues and manual such value is given without explaining for what power (%) has been obtained.

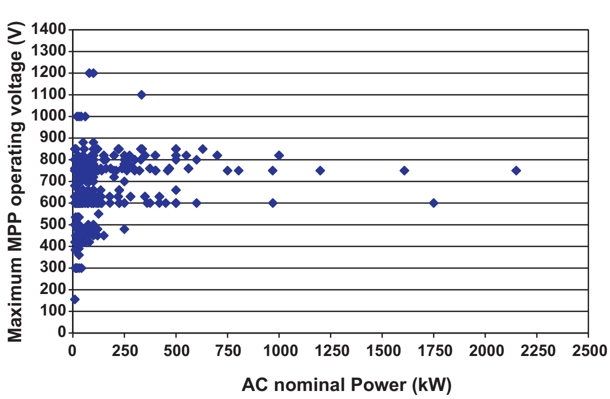

Fig. 9. Maximum power point voltage (V) vs AC nominal power (kW).

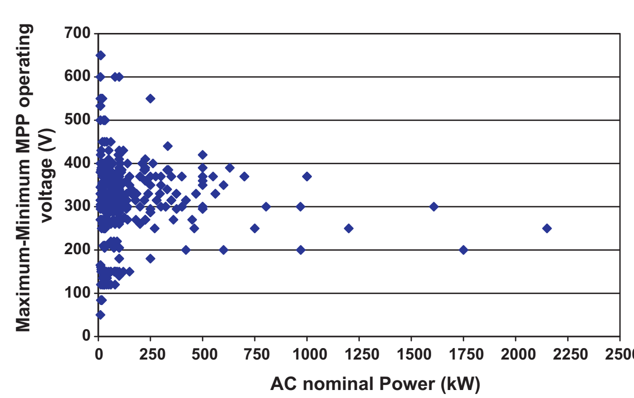

Fig. 10. Difference between maximum and minimum power point voltage (V).

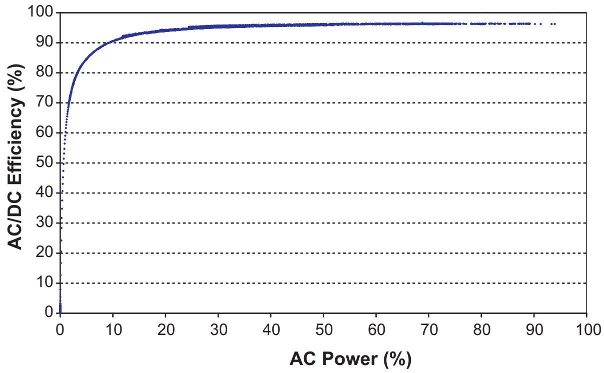

Fig. 11. Typical experimental AC/DC efficiency (%) with respect to AC power (W), for a generic grid-connected inverter.

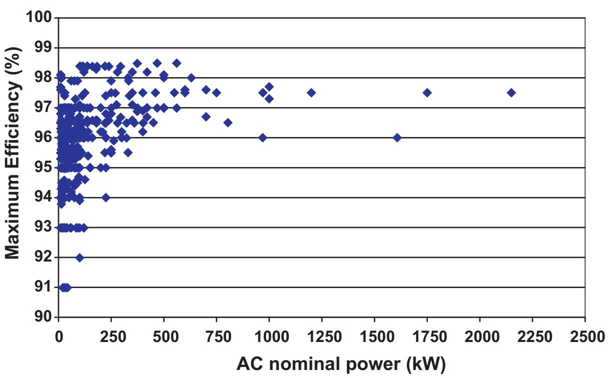

Fig. 12. Maximum efficiency (%) vs. AC nominal power (kW).

In Fig. 12 it can be observed that the efficiency range oscillates between 90.99% and 98.49%. Moreover, it is noticed that there is no relation with the AC nominal power (kW) because one can found low values for high AC nominal power.

On the other hand, the influence of the use or not of transformers in the inverters has been analyzed. From Fig. 13a–c can be viewed that for inverters with LF and HF transformer the maxima efficiency reached is 97.5%. For inverters with LF transformer is 98.1%. However for transformerless inverters the maxima efficiency reached is 98.49%, although only for some models, even for high values of power. However, it is noticed to mention that 94% is reached even for transformerless inverters. It means that depending of topology, control and transformer option chosen maxima efficiency close to 98% can be reached.

Another representative efficiencies which are used to compare different inverters, are the so-called 'California Energy Commission conversion efficiency', Eq. (1), and the so-called 'European efficiency', η_{EU}, Eq. (2) [21,22]. It was introduced in 1991 [4]. It is described in function of the efficiency at defined percentage values of nominal AC power as Eq. (1), where, as example, $\eta_{10\%}$ is the efficiency operating at 10% of the inverter nominal power.

$$\eta_{CA} = 0.04\eta_{10\%} + 0.05\eta_{20\%} + 0.12\eta_{30\%} + 0.21\eta_{50\%} + 0.53\eta_{75\%} + 0.05\eta_{100\%} \tag{1}$$

$$\eta_{EU} = 0.03\eta_{5\%} + 0.06\eta_{10\%} + 0.13\eta_{20\%} + 0.1\eta_{30\%} + 0.48\eta_{50\%} + 0.2\eta_{100\%} \tag{2}$$

Nevertheless, in both cases the weighting factors refer to the irradiance distribution concrete. Therefore, for example, the 'European efficiency' refers to irradiance distribution in north-western Germany at that time. Therefore they are not necessarily representative for all parts of Europe, especially for southern

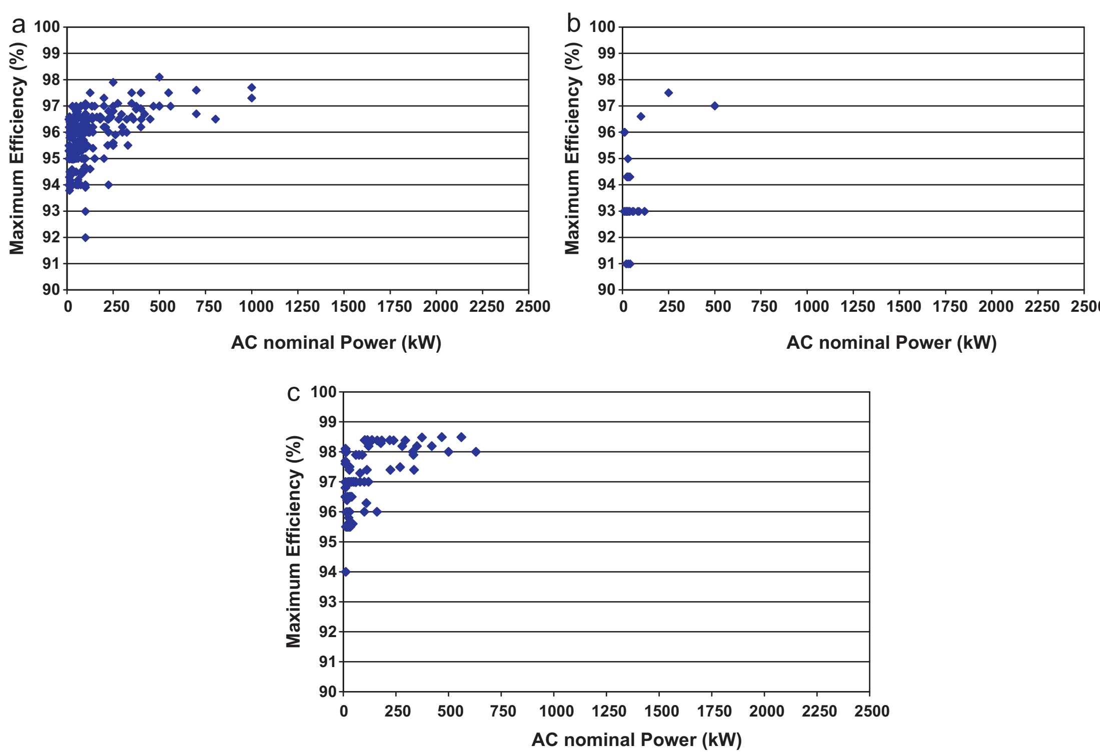

Fig. 13. (a) Maximum efficiency for inverters with LF transformers. (b) Maximum efficiency for inverters with HF transformers. (c) Maximum efficiency for inverters with transformerless.

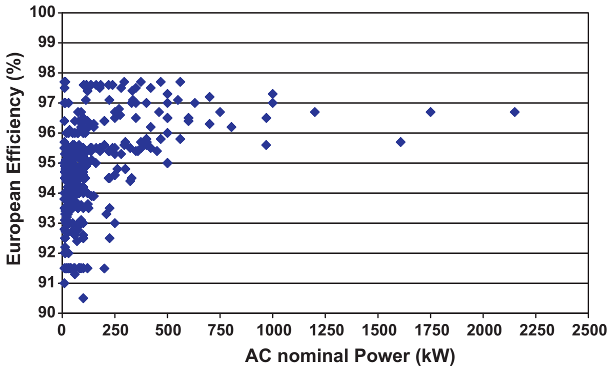

Fig. 14. European efficiency (%) vs AC nominal power (kW).

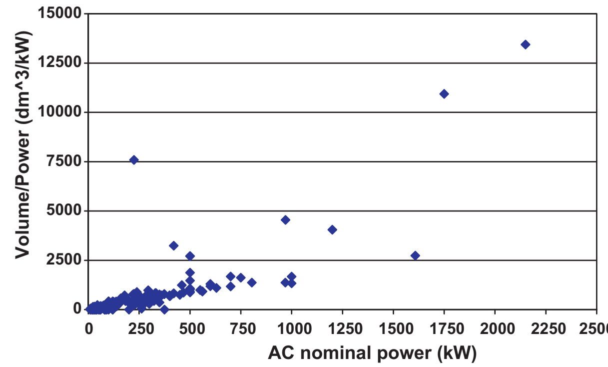

Fig. 16. Volume/power (dm^3/kW) vs AC nominal power (kW).

Europe. However, today it is a well established value for a quick comparison of conversion efficiency of inverters. In addition, it should be mentioned that η_{EU} can be an appropriate efficiency descriptor for PV systems with fixed angle structures for a general climate conditions. But, both local climatic conditions and type of tracking can influence the energy efficiency inverter. Nowadays the European efficiency is mostly used.

According to Fig. 14 European efficiency fluctuates between 89.5% and 97.7%. Although apparently there is no clear relation with the nominal power, it seems that the values of the such efficiencies increase, in a certain way, with the nominal power, although not in very homogenous way.

In addition the influence of the use or not of transformers in the inverters has been analyzed too, Fig. 15a–c. So, European efficiencies above 96% have not been found except for some brands of transformerless inverters which reach 98%. However also 88% values can be found for that type of inverters.

2.3. Other parameters

As well, other parameters such as volume and weight have been analyzed. In this way, normalised volume inverters have been analyzed, see Figs. 16–18. Next, it can be observed how a large majority of inverters have a volume/power ratio below two thousand. Thus, only sixty of them, 15.3%, have an upper ratio. Also it can be inferred that volume/power ratio is not proportional to the nominal output power.

In addition, normalised weight has been analyzed for every inverter, Figs. 19–21. These data show that there is great heterogeneity among them. Thus, there are inverters with lighter and less voluminous LF transformers than transformerless inverters. That means that contrary to common knowledge, it is not true to say that an inverter with an LF transformer has more volume and weight than an inverter with HF transformer, and at the same time an inverter with an HF

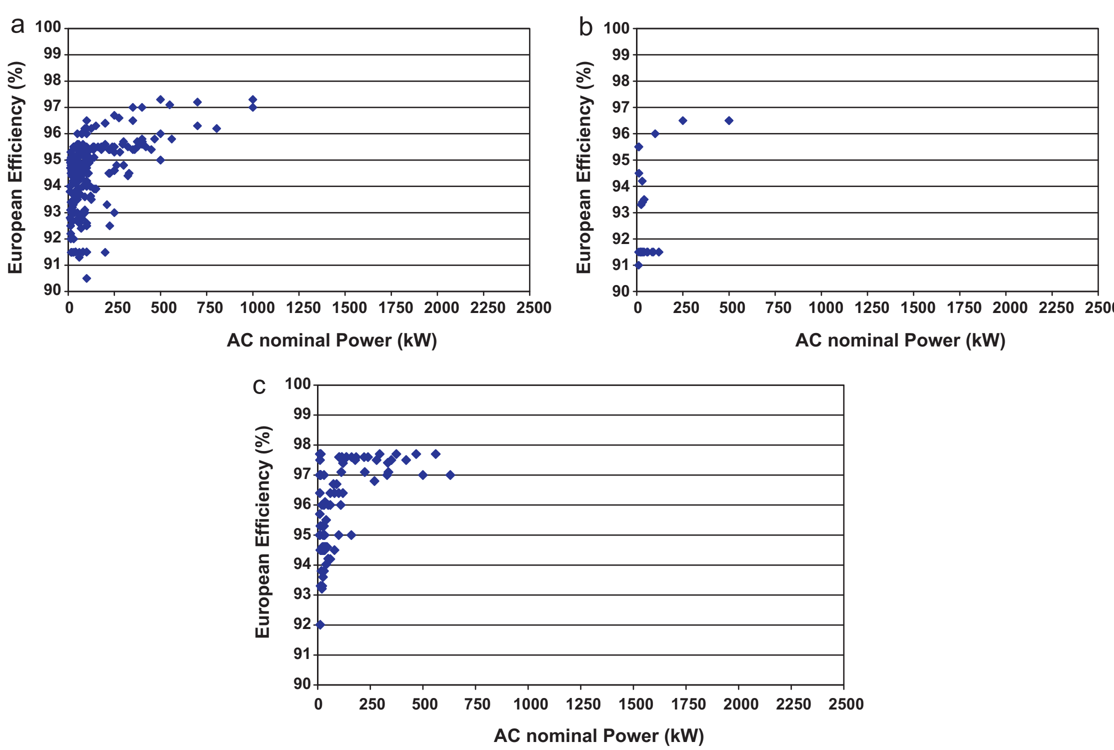

Fig. 15. (a) European efficiency (%) vs AC nominal power (kW) for inverters with LF transformer. (b) European efficiency vs AC nominal power (kW) for inverters with HF transformer. (c) European efficiency vs AC nominal power (kW) for inverters with transformer.

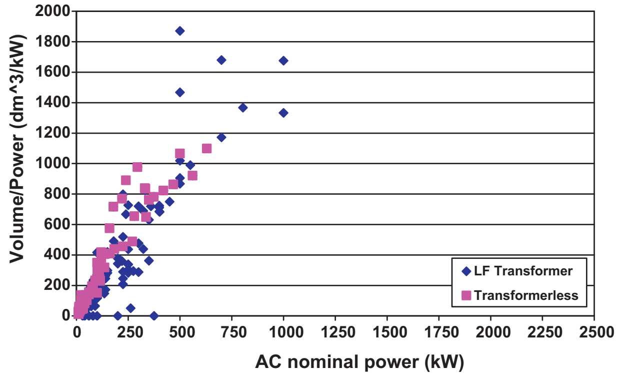

Fig. 17. Volume/power (dm^3/kW) vs AC nominal power (kW) for inverters with LF transformer and Transformerless.

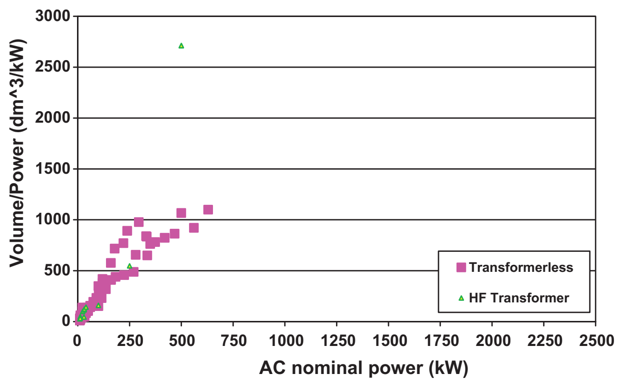

Fig. 18. Volume/power (dm^3/W) vs AC nominal power (kW) for inverters with HF transformer and Transformerless.

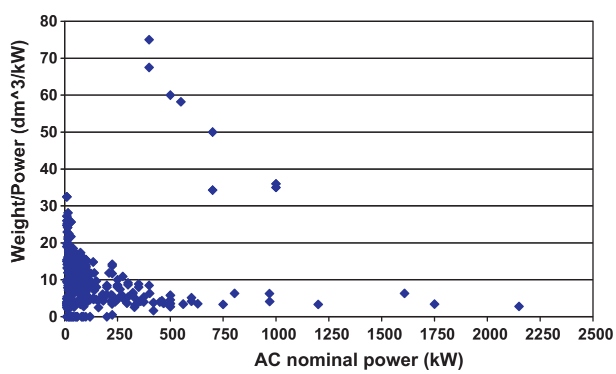

Fig. 19. Weight/power (kg/kW) vs AC nominal power (kW) for inverters with LF transformer and without transformer.

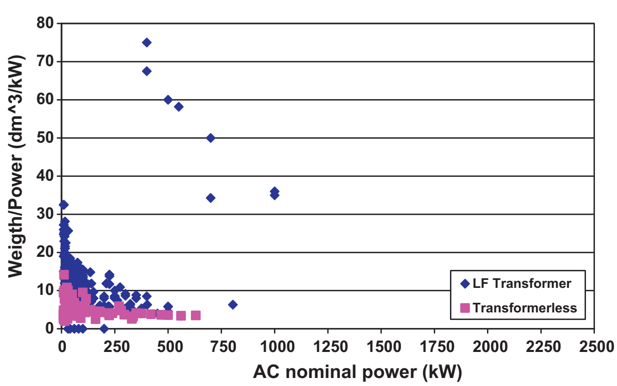

Fig. 20. Weight/power (kg/kW) vs AC nominal power (kW) for inverters with LF transformer and without transformer.

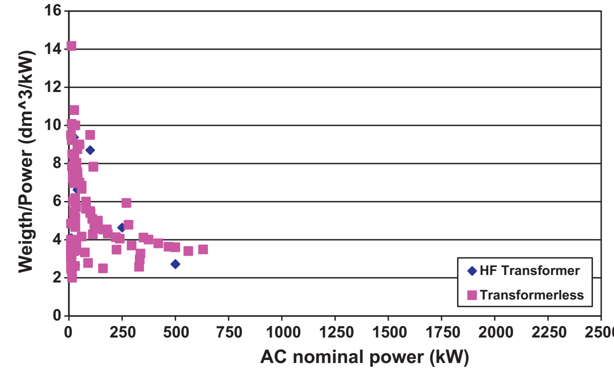

Fig. 21. Weight/power (kg/kW) vs AC nominal power (kW) for inverters with HF transformer and without transformer.

transformer has more volume and weight than a transformerless inverter.

3. Conclusions

According to the obtained results the following conclusions can be made: Different ranges of nominal AC power have been found, between 10 and 2150 kW. The AC nominal power inverter most used was 100 kW, that is for thirty-six models, 12.16% of the total inverters; followed by the inverters of 50 kW (6.42%) and 30 kW (5.41%). nominal AC power inverters below 100 kW representing 71%. Likewise, it has been possible to verify that 100% of the studied inverters are three-phase, which was expected for this power range. And most of inverters are boost inverters.

In addition, regarding the efficiency, the evolution of the efficiency versus power hardly ever is given in manuals and catalogues. Instead of three efficiencies values are given by manufacturers: maximum efficiency, European efficiency and rarely the 'California Energy Commission conversion efficiency'. Regarding maximum efficiency, it is a value that by itself offers very little information because is not given for what value has been obtained. However, it has been possible to find that maximum efficiency oscillates between 90.99% and 98.49%. The values of these efficiencies are increased, more or less, with the nominal power, although not in a very homogenous way. Also, it has been proven that the maximum efficiency does not depend on transformer options of inverter.

On the other hand, the European efficiency is a parameter whose weighting factors refer to the irradiance distribution in north-western Germany. But it varies according to local climatic conditions and type of tracking used. Their values fluctuate between 89.5% and 97.7%. Although apparently there is no clear relation with the nominal power, it seems that the values of the such efficiencies increase, in a certain way, with the nominal power, although not in very homogenous way. Again, there is no relation to transformer option used by every inverter.

In addition, it has been possible to corroborate that the normalised volume and weight is very heterogeneous. Finally, it has been verified that three different topologies exist: inverters with a transformer of LF, a transformer of high frequency and inverters without a transformer, representing 70, 7 and 23%, respectively. These numbers confirm the boom that inverters without transformers have been experiencing in recent years. As well, against common knowledge, it is not true to say that an inverter with an LF transformer has more volume and weight than an inverter with HF transformer, and at the same time an inverter with an HF transformer has more volume and weight than a transformerless inverter.

Acknowledgments

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